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Variation in atmospheric dust since 1950 from an ice core in the Central Tibetan Plateau and its relationship to atmospheric circulation

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ABSTRACT

Variation in atmospheric dust deposited on the Tibetan Plateau (TP) and its response to climate change are not well understood. In this study, a 65-year annually resolved (1950–2014) atmospheric dust proxy record is presented from the Mugagangqiong (MGGQ) ice core in the central Tibetan Plateau. There is a significant positive correlation between the dust concentration of the MGGQ ice core and dust days observed from meteorological stations in the Taklimakan Desert ($r = 0.47$, $p < 0.001$) and the central TP ($r = 0.50$, $p < 0.001$), indicating that the MGGQ dust record provides a good proxy for reconstructing an annual history of atmospheric dust-loading in this region. Two periods of enhanced dust deposition, (1962–1968 and 1975–1987), characterised by high concentrations and coarse grain size, suggest enhanced aridity, strong winds and active dust storm events. The lowest dust deposition period was identified as being between 1988 and 2000. Here we utilise 1975–1987 and 1988–2000 as typical high and low dust-loading periods, respectively, to discuss the possible dust mechanisms with the JRA-55 reanalysis data. During the high dust-loading period, dust concentration and flux were positively correlated with the mid-latitude zonal wind, suggesting that the high-level westerlies strengthened in northwestern China and transported more dust to the central TP than during the low dust-loading period. Dust concentration and flux decreased from the late 1980s and were positively correlated with weakened zonal winds and negatively correlated with precipitation in northwestern China from 1988 to 2000. Weakening westerlies and increasing precipitation at the dust source areas were responsible for this decrease in dust-loading during this period.

1. Introduction

Mineral dust plays a key role in the global climate system. It can influence the atmospheric radiation budget and hydrological cycle by its radiative effects and cloud condensation nucleus effect (Forster and Ramaswamy, 2007; Ji et al., 2016; Tang et al., 2018; Tegen et al., 1996). Atmospheric dust particles have an impact on atmospheric chemical reactions and affect ocean biogeochemistry by acting as a source of nutrients (Jickells et al., 2005; Li et al., 2017; Zhang and Carmichael, 1998). In addition, dust particle deposition onto the snow surface can reduce snow albedo and enhance subsequent glacier melting (Fujita, 2007; Yasunari et al., 2011).

The Tibetan Plateau (TP) is adjacent to arid and semi-arid areas in Central Asia. Its numerous glaciers, with an average elevation of ~4000 m, provide an ideal medium for the study of dust records from ice cores at mid-low latitudes. Over the last few decades, scientists have obtained dozens of ice cores of various lengths at different sites there, such as Guliya, Dunde, Puruogangri (Thompson et al., 2006a; Thompson et al., 2006b; Thompson et al., 1997), Malan (Wang, 2005), Zangser Kangri (Zhang et al., 2016), Geladaindong (Grigholm et al., 2015; Kang et al., 2010), Tanggula (Wu et al., 2013), Dasuopu (Thompson et al., 2000) and East Rongbuk Ice Core (Xu et al., 2010). These ice cores provide high-resolution pre-instrumental dust records at different timescales, which deepens understanding of atmospheric dust variability and environmental evolution on the TP. Dust records in Tibetan ice cores show notable temporal and spatial variations. Over the past few decades, annual mean dust concentration/flux of the northern and northwestern TP ice cores was two to ten times higher than the

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southern ice cores (Wu et al., 2010). However, discrepancies in dust temporal variation among the ice cores in the same region remain, such as Puruogangri, Geladaindong and Tanggula ice cores, located in the central TP (Thompson et al., 2006b; Wu et al., 2013; Zhang et al., 2015). The reason for these discrepancies is still unknown. In recent years, various studies have used reanalysis data to reveal the relationship between the ice core dust record and atmospheric circulation (e.g. Kang et al., 2010; Kang et al., 2003). In addition, research suggests that there are potential teleconnections between Asian dust records and climate indices (such as NAO, PDO) (Grigholm et al., 2009; Xu et al., 2007; Zhang et al., 2015).

Modern ice core dust records can be calibrated using in situ observations, making it possible to accurately understand the long-term climate and environmental changes retrieved from ice cores. The central part of the TP is a critical area for interactions between the westerlies and Indian monsoons. Temporal changes in atmospheric dust in this region and their controlling factors are not yet clear. In this study, atmospheric dust records from the Mugagangqiong ice core in the central TP over the 65-year period 1950–2014 were retrieved to reveal the dust history of the region. The relationship between dust and atmospheric circulation based on The Japanese 55-year (JRA-55) reanalysis data is discussed, which will help understand the mechanism of atmospheric circulation affecting dust variation in the central TP over the past few decades.

2. Methodology

2.1. Ice coring and experimental method

In October 2014, an 82.08 m ice core (32.24°N, 87.48°E, 6085 m a.s.l.) was recovered from the accumulation zone of Mugagangqiong (MGGQ) Glacier in the central TP (Fig. 1). Sealed in clean polyethylene bags, the ice core sections were transported in frozen form to the Key Laboratory of Tibetan Environment Changes and Land Surface Processes (TEL, Chinese Academy of Sciences, Lhasa, China), and kept in a refrigerator at temperatures below −20 °C. The ice core sections were sequentially cut with sub-annual resolution at intervals of 3 cm in the upper 40 m and at intervals of 2 cm in the lower 42 m; a total of 3414 samples were obtained. Approximately 8 mm from the outer part of each sample was removed using a clean stainless steel scalpel. The inner part of the core was divided into three vials for the analysis of insoluble particles, ions and oxygen/hydrogen isotopes. The measurement of oxygen isotope was conducted using a Picarro L2130-I Analyzer (Picarro INC., U.S.A.) at TEL, Beijing. Microparticle concentration and grain-size distribution were measured using a Beckman Coulter Counter Multisizer 3 with an aperture of 50 μm (size range between 1 and 30 μm in diameter) in a class 1000 clean room at TEL, Lhasa. Scraped ice chips were collected for β-activity measurements, using a Mini 20 alpha-beta Multidetector (Eurisys Measures) at the State Key Laboratory of Cryospheric Science (SKLCS), CAS, Lanzhou. The pre-treatments and detailed measurements have been described in detail in previous studies (Wu et al., 2010; Wu et al., 2009).

2.2. Ice core dating

The annually resolved timescales for the upper 10 m of MGGQ ice core were determined back to 1949 by counting the seasonal minimums in the concentration and mean number diameter of dust particles (Fig. 2). The variation of $\delta^{18}O$ was often used to identify annual cycles in ice core dating, while the seasonal $\delta^{18}O$ distribution did not exhibit clear peaks or valleys in the MGGQ ice core. The maximum peak of β radioactivity appeared at 7.59–9.01 m, which indicates the fallout from nuclear bomb testing in 1963. By counting the annual layers, the depth of 7.93 m was identified as a reference horizon for 1963 to calibrate the annual dating of the ice core.

Based on monthly blowing dust days in meteorological stations in the central TP (Fig. 3), the dusty period occurs during the winter/non-monsoon season (November to April), and the non-dusty period during the summer/monsoon season (May to October). This seasonal difference therefore gives a reference for annual dating, and the valley in dust concentration most likely corresponds to the monsoon season. An ice flow model was performed to calibrate MGGQ ice core dating below 10 m and to calculate the annual accumulation rate (water equivalent) (Bolzan, 1985). The annual deposition flux of dust was obtained by multiplying the dust mass concentration and accumulation rate. In this study, we focus on records in the upper 9.77 m, which spans from 1950 to 2014.

3. Results and discussion

3.1. Dust record from 1950 to 2014

The time series of dust and $\delta^{18}O$ records at intervals of 3 cm from the MGGQ ice core are presented in Fig. 4, including dust mass concentration (MC), number concentration (NC) and mean number diameter (MND). With a range from 10^4 to 10^6 ml^{-1} and from 10^3 to 10^5 μg/kg, the NC and MC vary greatly among dust samples. In contrast, MND varies from 1.62 μm to 2.34 μm with a very small standard deviation. The annual values of dust variables are summarised in Table 1. The annual mean NC and MC of the MGGQ ice core are close to that of the Tanggula ice core (annual mean NC is 183,803 ml^{-1} and MC is 10,058.9 μg/kg, 1950–2004) (Wu et al., 2013). In the 65-year period 1950–2014, annual dust-deposition flux in MGGQ was 110.15 μg cm^{-2} a^{-1}, which is comparable to the Tanggula ice core (219.82 μg cm^{-2} a^{-1}). It is lower than the Dunde (798 μg cm^{-2} a^{-1}) and Muztagata (342 μg cm^{-2} a^{-1}) ice cores in the northern and western TP, but higher than the Dasuopu (77 μg cm^{-2} a^{-1}) and Everest (103 μg cm^{-2} a^{-1}) ice cores in the southern TP (Wu et al., 2010). Thus, compared with the southern and northwestern TP, the deposition of dust in glaciers in the central region of the plateau is moderate. This conclusion is consistent with previous findings (Wu et al., 2010). The ice cores in the northwestern parts of the TP are in the vicinity of major dust source areas (the arid and semi-arid areas of northwestern China, including the Taklimakan Desert and Qaidam Basin Desert, etc.), while the ice cores in the southern TP are distant from the major dust source areas. As westerly winds prevail over the TP throughout the year, these results suggest that dust source distribution, transport distance and atmospheric circulation all have an impact on ice core dust deposition.

Dust flux in ice cores can be an indicator of the aridity in source region (Wu et al., 2013), and MND of dust indicates the wind strength (Zielinski and Mershon, 1997). From 1950 to 2014, there is a positive correlation between dust flux and MND of MGGQ ice core ($r = 0.36$, $p < 0.01$). It means that when aridity increased, wind strength usually enhanced on inter-annual scale, which can also be seen in the Tanggula ice core (Wu et al., 2013). Grain-size characteristics of dust particles in the ice core can show the way they have been transported. Due to the high altitude, fine particles (e.g. < 5 μm) deposited in ice cores are mostly from long-range dust transport, while coarse particles (e.g. > 15 μm) are mostly from severe dust storms and/or local material (Zhang et al., 2015; Maring et al., 2003). No significant correlation is found between the ratio of coarse particles to total mass in the MGGQ ice core and dust day records from meteorological stations in Taklimakan Desert and the central TP (meteorological data can be accessed from China National Meteorological Data Service Center, http://data.cma.cn/en). Therefore, the coarse particle ratio may indicate the relative contribution of local dust. Fine particles with a diameter < 5 μm account for 96.4% of total number, while coarse particles with a diameter > 15 μm account for only 0.10% of the total number, but contribute 16.0% to the total mass in the MGGQ ice core. The mass contribution of coarse particles in MGGQ ice core is similar to the Tanggula ice core (17.4%), but higher than the Dunde (8.2%) (Wu et al., 2010) and Zangser Kangri (9.7%) (Zhang et al., 2016). These ice core records

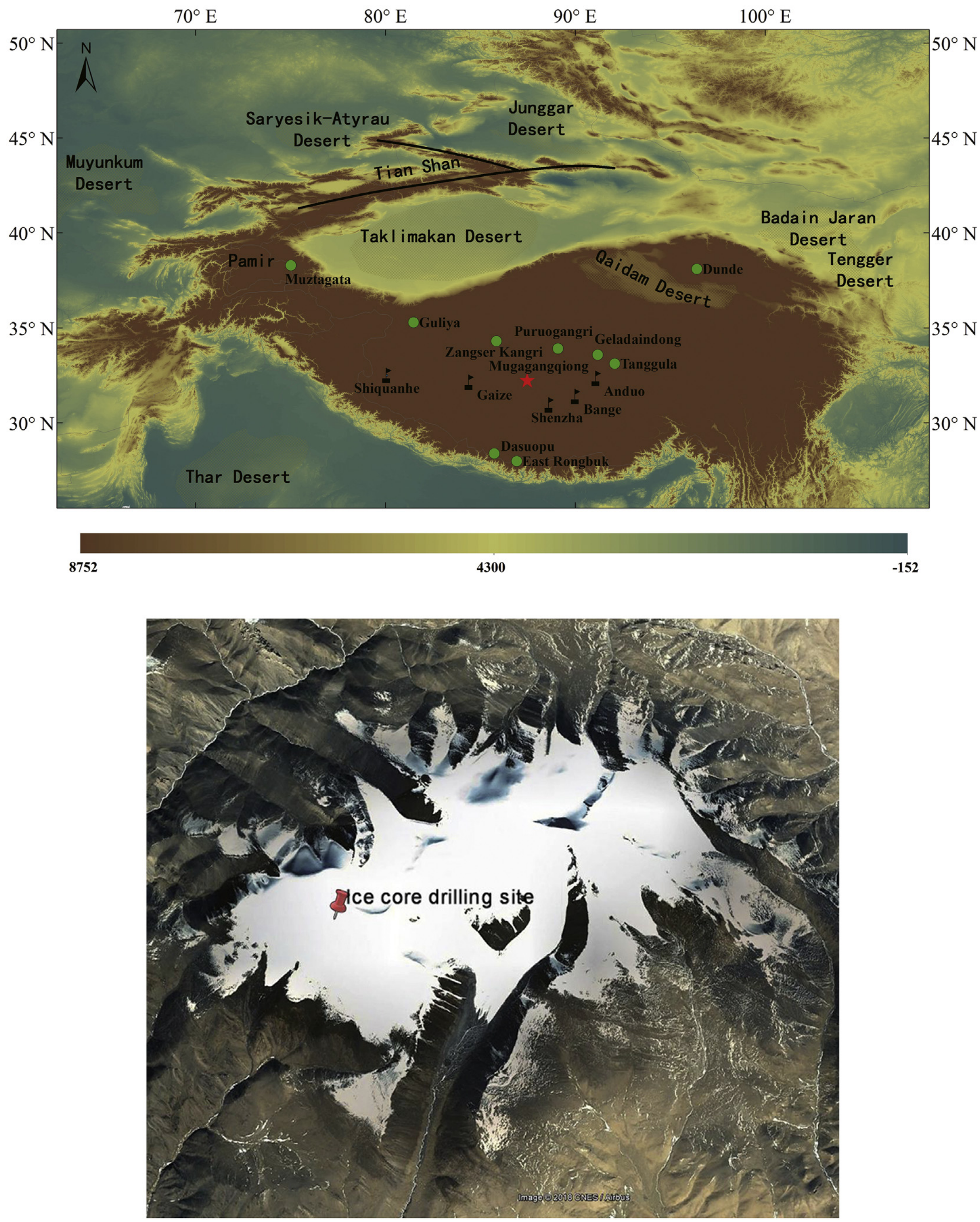

Fig. 1. Map of the Mugagangqiong Ice Core drilling site (red star) and the selected meteorological stations (black flags) in the central Tibetan Plateau. The map also marks other ice core sites mentioned in the text (green dots). (For meteorological stations, Shiquanhe: 32.5°N, 80.08°E, 4278 m a.s.l., time period 1961–2005; Gaize: 32.15°N, 84.42°E, 4415 m a.s.l., time period 1973–2005; Amdo: 32.35°N, 91.10°E, 4800 m a.s.l., time period 1966–2005; Bange: 31.38°N, 90.02°E, 4700 m a.s.l., time period 1957–2005; Shenzha: 30.95°N, 88.63°E, 4672 m a.s.l., time period 1961–2005.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

show that the contribution of local material to dust mass in ice cores in the central TP is higher than that of the northern regions. From the 1980s to 2011, the ratio of coarse particles to total mass was higher than the average value of the 65-year period 1950–2014 (Fig. 5a). MND also increased significantly from 1995 to 2008 (Fig. 5b) and was positively correlated with the mass ratio of coarse particles ($r = 0.39$, $p < 0.05$), indicating that local dust particles made a substantial contribution to dust grain size in MGGQ ice core during this period.

3.2. Comparison with meteorological data and reanalysis data

From 1950 to 2014, there were two periods of dustiness, 1962–1968 and 1975–1987, with increased dust concentration, flux and MND (Fig. 5). 1975–1987 was the period with the highest dust concentration and flux in the MGGQ ice core: the NC is 271,421 ml^{-1}, and flux is 174.22 $\mu g\ cm^{-2}\ a^{-1}$. Meanwhile, the period 1975–1987 had the most blowing dust days at meteorological stations in the central plateau (average of five meteorological stations: Shiquanhe, Shenzha, Gaize, Anduo and Bange) (Fig. 5e) over the 50-year period 1964–2014. The annual average of meteorological data is calculated in this paper as the mean value from August to July, to compare it with the ice core records. Dust storms (sum of blowing sand and sandstorms) occurred frequently in the Taklimakan Desert (the dust source areas) during the two periods of dustiness (Fig. 5c) (Yang et al., 2016). During these two periods, the

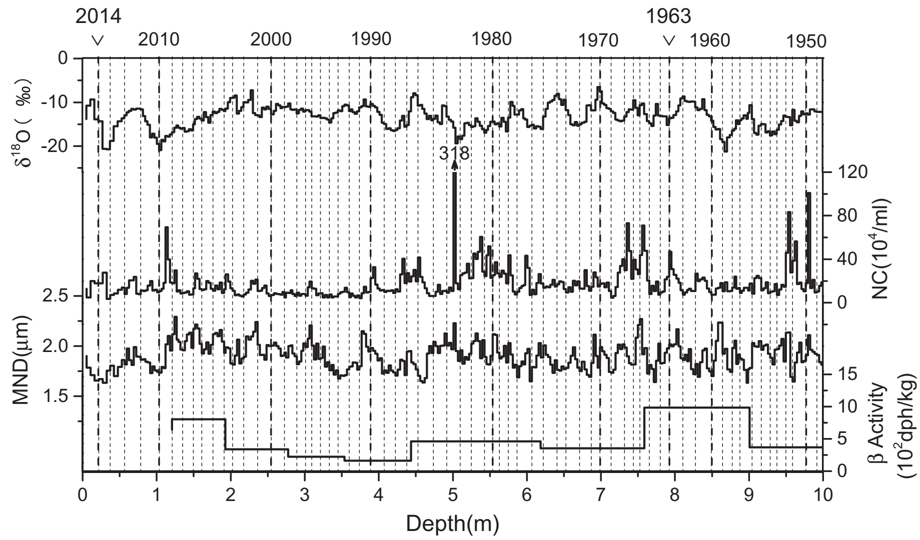

Fig. 2. Dating of the Mugagangqiong Ice Core by the seasonal variation in microparticle number concentration (NC), mean number diameter (MND) and $\delta^{18}O$ isotope. The 1963 β-activity horizons are also presented.

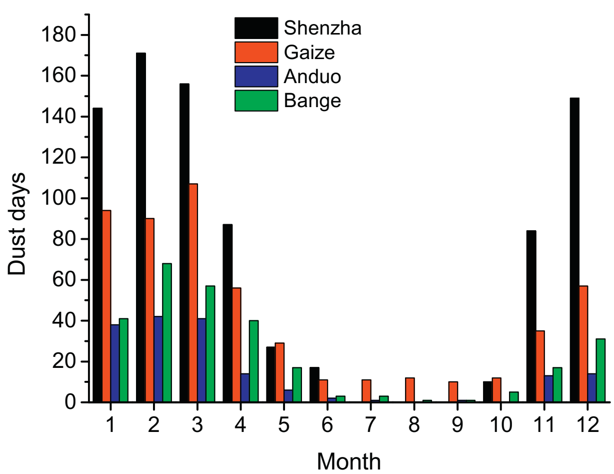

Fig. 3. The monthly blowing dust days at meteorological stations (Shenzha, Gaize, Anduo, Bange) in the central Tibetan Plateau (1961–2005).

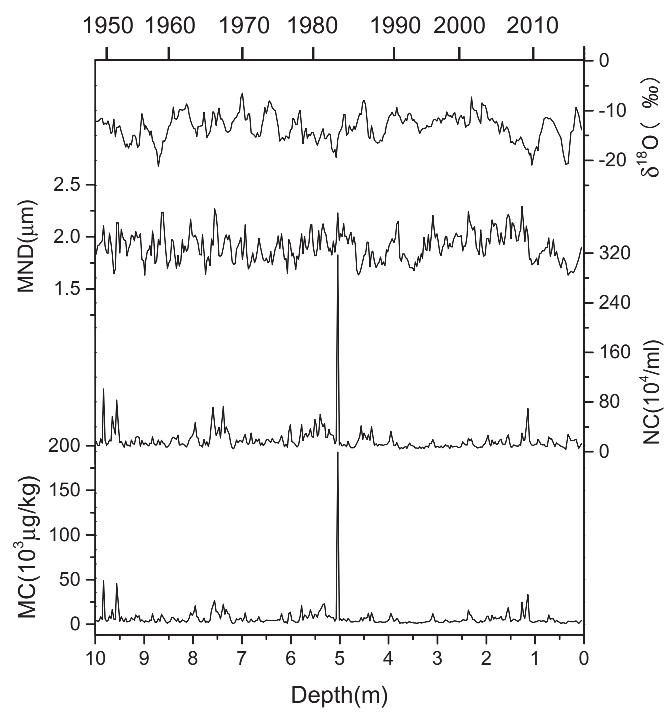

Fig. 4. Time series of dust records in the Mugagangqiong Ice Core (with raw data) (MND, mean number diameter; NC, number concentration; MC, mass concentration).

climate was characterised by enhanced aridity, strong winds and frequent dust storms. There is a positive correlation between the NC and dust storm activities in the Taklimakan Desert ($r = 0.47$, $p < 0.001$). The MGGQ dust NC ($r = 0.50$, $p < 0.001$) and flux ($r = 0.40$, $p < 0.01$) were also positively correlated with dust days from five meteorological stations in the central TP. This indicates that dust records of the MGGQ ice core are good indicators of the variation of atmospheric dust in this region.

It is noteworthy that from 1988 to 2014, apart from 2009, dust NC in MGGQ ice core was below the average of the 65-year period. Dust flux was also significantly low during this period. The lowest value of dust NC and flux appeared during the period 1988 to 2000 (annual average of NC and flux were 96,788 ml^{-1}, 54.55 $\mu g\, cm^{-2}\, a^{-1}$, respectively). There was a substantial increase in the frequency of blowing dust in meteorological stations in the late 1970s, however, it gradually decreased from the 1980s in the central TP (Fig. 5e). The decline in both dust concentration and flux in ice cores and in dust storm events observed from meteorological stations implies there have been notable changes in climate and environment in this region since the 1980s. Monitoring and modelling of the atmospheric dust shows that dust emission from arid and semi-arid areas in Asia began to decrease since the 1970s, and the decreasing trend continued to the beginning of 21st century (Shao and Dong, 2006; Wang et al., 2017; Zhang et al., 2003). In the Taklimakan Desert, dust storms were active in the 1960s and 1970s, and from 1987 the frequency fell below the

Table 1
Annual mean value of dust variables in the Mugagangqiong ice core.

	MND	NC	MC	Flux
	μm	mL^{-1}	μg/kg	$\mu g\, cm^{-2}\, a^{-1}$
Mean	1.92	185,022	8239.1	110.15
Min	1.69	60,100	1994.1	21.43
Max	2.19	636,738	45,027.8	748.24
SD	0.11	111,852	6652.9	99.26

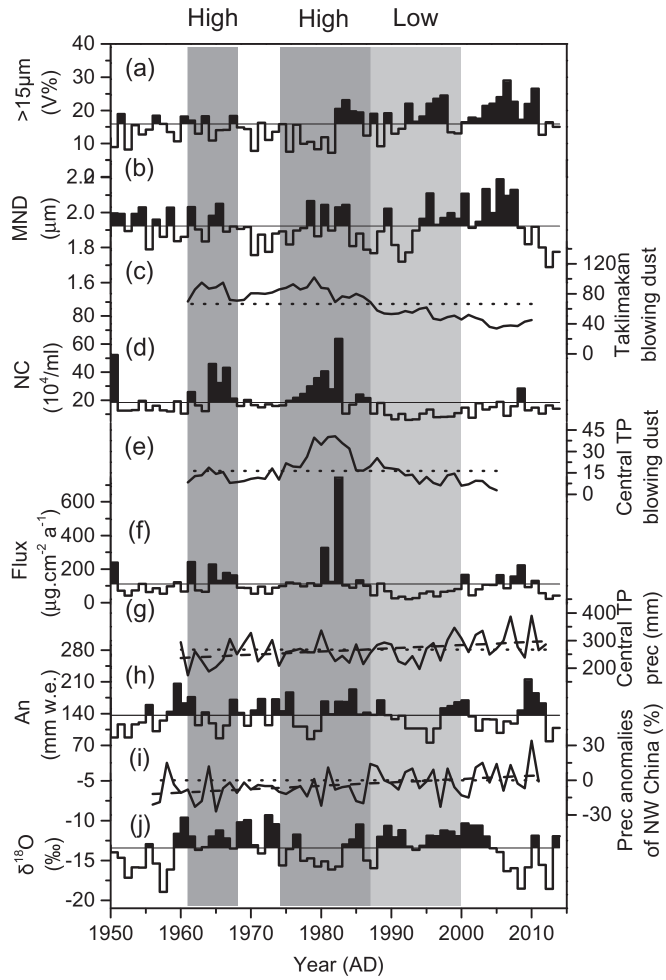

Fig. 5. The annual average of proxies in the Mugagangqiong Ice Core (values greater than the annual average (1950–2014) are filled with solid black) compared with other records, including dust storm days from meteorological stations in Taklimakan Desert (c) (Yang et al., 2016), blowing dust days (e) and precipitation (e) from meteorological stations in the central Tibetan Plateau (the average annual value is calculated from August to July) and precipitation anomalies of northwestern China (i) (the average annual value is calculated from June to May) (Ren et al., 2016) (dotted line represent the average level, dashed line indicates the linear trend).

average (Fig. 5c) (Yang et al., 2016). Dust particles can be reduced by the rainout process in the atmosphere. Meanwhile, more precipitation contributes to moister environments in the dust source area, which results in a lower drought index and reduced dust emission (Huang et al., 2017). Meteorological data and the National Centers for Environmental Prediction–National Center of Atmospheric Research (NCEP–NCAR) reanalysis data show that both precipitation and moisture transport in northwestern China (especially the western areas) gradually increased since the late 1970s (Fig. 5i), and there has been a sudden increase in precipitation extremes since the mid-1980s (Chen et al., 2014; Ren et al., 2016). Although the accumulation in the MGGQ ice core did not show any variation tendency, the increase of precipitation at five meteorological stations in the central TP was evident (Fig. 5g).

The reduction in dust storms and increasing precipitation in dust source areas might be the reason for the decrease of dust-loading in northwestern China (including TP). From the dust records of the MGGQ ice core and meteorological data we can see that the decrease in atmospheric dust-loading started from the 1980s in the central TP. But there is no steadily decreasing trend in the dust NC and flux of the MGGQ ice core. The NC has shown a slowly increasing tendency since 2000, though it is still below the average of the 65-year period. Dust flux increased from 1992, but began to decline again from around 2010. However, compared with the mean value of the period studied, it is evident that atmospheric dust-loading has been at a considerably low level from the late 1980s to the beginning of the 21st century. The reduction of atmospheric dust is noteworthy because it may indicate a dramatic change in climate and environment related to 20th century warming trends on the TP.

3.3. The relationship between atmospheric dust and atmospheric circulation

The changes in atmospheric circulation determine the transport pathways and intensity of atmospheric dust, thus affecting dust deposition on the TP. In this paper we selected the periods of the highest (1975–1987) and the lowest (1988–2000) dust-loading as two cases to investigate the impact of atmospheric circulation variations on dust deposition in the central TP. The JRA-55 reanalysis data from the Japan Meteorological Agency (JMA) was used to analyse the climatological factors, including wind and precipitation. The annual mean value was calculated by averaging monthly data (August to July). The duration of the JRA-55 data is from 1958 to 2014, and its grid resolution is 1.25° × 1.25° (Harada et al., 2016; Kobayashi et al., 2015) (http://jra.kishou.go.jp/JRA-55/index_en.html). Annual mean wind field at 400 hPa of these two periods can be seen in Fig. 6a. It is clear that the prevailing westerly wind is dominant in the both periods over the TP, and the general atmospheric circulation is basically the same. Differences can be seen by subtracting the period of low dust-loading from that of high dust-loading (Fig. 6b). Compared with the period of low dust-loading, northwesterly wind in the area where the ice core is located is stronger in the period of high dust-loading. Further, northerly/northwesterly wind in the dust source area (northwestern China, including the TP) and arid and semi-arid areas in the eastern part of Central Asia has evidently strengthened. Although the Iran Plateau and India (e.g. the Thar Desert) are potential dust source areas (Xu et al., 2012; Kaspari et al., 2009), during the period of high dust-loading, zonal wind in these areas weakens. Student's *t*-test of significance of wind field difference (wind direction and wind speed) between the high and low dust-loading periods shows that wind speeds in potential source areas including the Taklimakan Desert and the arid and semi-arid areas around western Tianshan Mountains are significantly different (reaching the 90% confidence level, Fig. 6d). As mentioned above, dust events frequently occurred in the Taklimakan Desert and in the central TP from 1975 to 1987 (Fig. 5c, e). Therefore, compared with 1988–2000, northerly/northwesterly wind strengthened in the source areas and transported more dust to the central TP from 1975 to 1987.

To further understand the relationship between atmospheric circulation and dust records, spatial correlation analysis was conducted on the relationship between the dust NC/flux and zonal wind. From 1958 to 2014, there was no correlation between the dust NC/flux and zonal wind. This means that apart from wind speed, there are other factors that can affect dust variation in different periods. However, the dust NC and flux are positively correlated with mid-latitude zonal wind during the period of high dust-loading, with a correlation coefficient higher than 0.4 ($p < 0.05$) in northwestern China (Fig. 7a, b). During the period of low dust-loading, the dust NC/flux is positively correlated with zonal wind in northwestern China, particularly in the Taklimakan Desert ($r = 0.4$, $p < 0.05$, Fig. 7c, d). The correlation between dust records of the MGGQ ice core and zonal wind in northwestern China indicates that the arid and semi-arid areas in northwestern China make important contributions to atmospheric dust deposition in the central TP.

To analyse the impact of precipitation on dust variability, spatial correlation between the dust NC/flux and precipitation was also conducted. The NC and flux are positively correlated with precipitation in northwestern China in the period of high dust-loading. However,

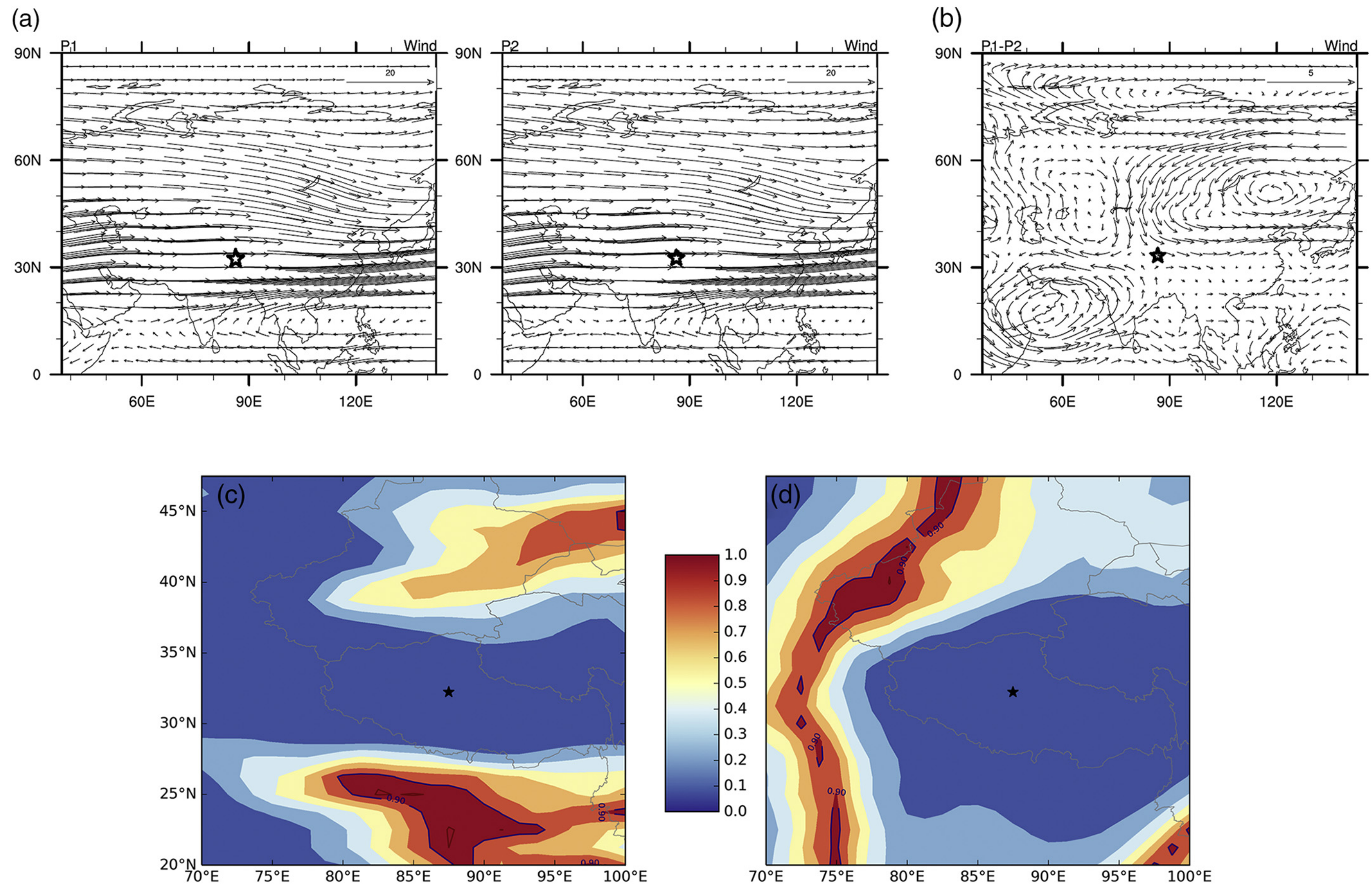

Fig. 6. Average 400 hPa wind field of the high dust period (P1,1975–1987) and the low dust period (P2,1988–2000)(a), and the wind field of high minus low period (P1-P2)(b); Student's *t*-test of significance of the difference of the wind direct (c) and the wind strength (d) between high and low periods.

precipitation usually has a negative correlation with dust flux and NC, and this observed positive correlation might not indicate a connection to the mechanism of action. During the period of low dust-loading, the dust NC/flux and precipitation in arid and semi-arid areas of northwestern China are negatively correlated (the correlation coefficient of dust flux and precipitation is about -0.6, $p < 0.05$, Fig. 8b). These results indicate that westerly wind speed in the dust source area (particularly northwestern China) is the main factor which determines dust variation from 1975 to 1987 in the central TP, while during the period 1988–2000, precipitation also had a significant impact on dust variation.

Dust storm activity and precipitation determine dust-loading in the atmosphere, while dust storm activity and variations in precipitation are also controlled by the large-scale circulation system. Research suggests that climatic fluctuations (e.g. temperature, wind strength, precipitation) are the major factors controlling the declining trend in dust activity observed at meteorological stations in Asia (Goudie, 2009). Wang et al. (2018) suggested that a steady decrease in zonal maximum wind speed in the Northern Hemisphere is responsible for the decline of dust events over northwestern China. The amplitude of this decreasing trend grew slowly prior to the 1980s but became much more rapid in mid-latitude areas after the 1980s, concurrent with fewer dust events as indicated by the dust NC and flux in the MGGQ ice core and meteorological data (see section 3.1). Moreover, wind strengthened slightly in the 1960s (Wang et al., 2018), which can also be seen in the MGGQ ice core and meteorological data (Fig. 5). Meteorological and reanalysis data (e.g. JRA-55, NCEP-NCAR) also show that surface wind and upper-air wind in most parts of China gradually decreased from 1960 to 2009, and this decreasing trend was more significant in the TP (Lin et al., 2013). The decrease in dust events in Northern China after the 1980s was due to the weakening of the westerly jet stream and a shift in geopotential height over the Mongolian plateau, which led to decreased surface wind speeds (Zhu et al., 2008). Wang et al. (2018) also argued that the significant changes in dust events were not controlled by dry land expansion but mainly controlled by the wind strength. Dry land in China expanded while precipitation increased over the past few decades (Huang et al., 2017). Based on the dust record in the MGGQ ice core, the westerly wind weakened in the low dust-loading period compared with the high dust-loading period, and changes in the dust NC/flux in the MGGQ ice core coincide with westerly wind variation in the source areas (i.e., northwestern China) during both periods, which is consistent with the research mentioned above. We also note that dust flux in the MGGQ ice core is negatively correlated with precipitation ($r = -0.6$, $p < 0.05$). Thus, the weakening westerly wind in the mid-high latitudes (especially in northwestern China) is likely the major reason for the reduction in dust events since the 1980s. Furthermore, increasing precipitation led to the decline of atmospheric dust-loading, which accordingly lowered the dust concentration and flux in the MGGQ ice core.

3.4. Possible correlation with climate index?

North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) are two of the most important climate indices in the northern hemisphere that can influence dust transport. Dust records of the Geladaindong ice core in the central TP are positively correlated with the NAO and PDO (Grigholm et al., 2009; Zhang et al., 2015), while dust concentration in the East Rongbuk ice core of Mt. Qomolangma is negatively correlated with NAO (Xu et al., 2007). But some cases do not show any correlation, such as the Tanggula ice core (Wu et al., 2013).

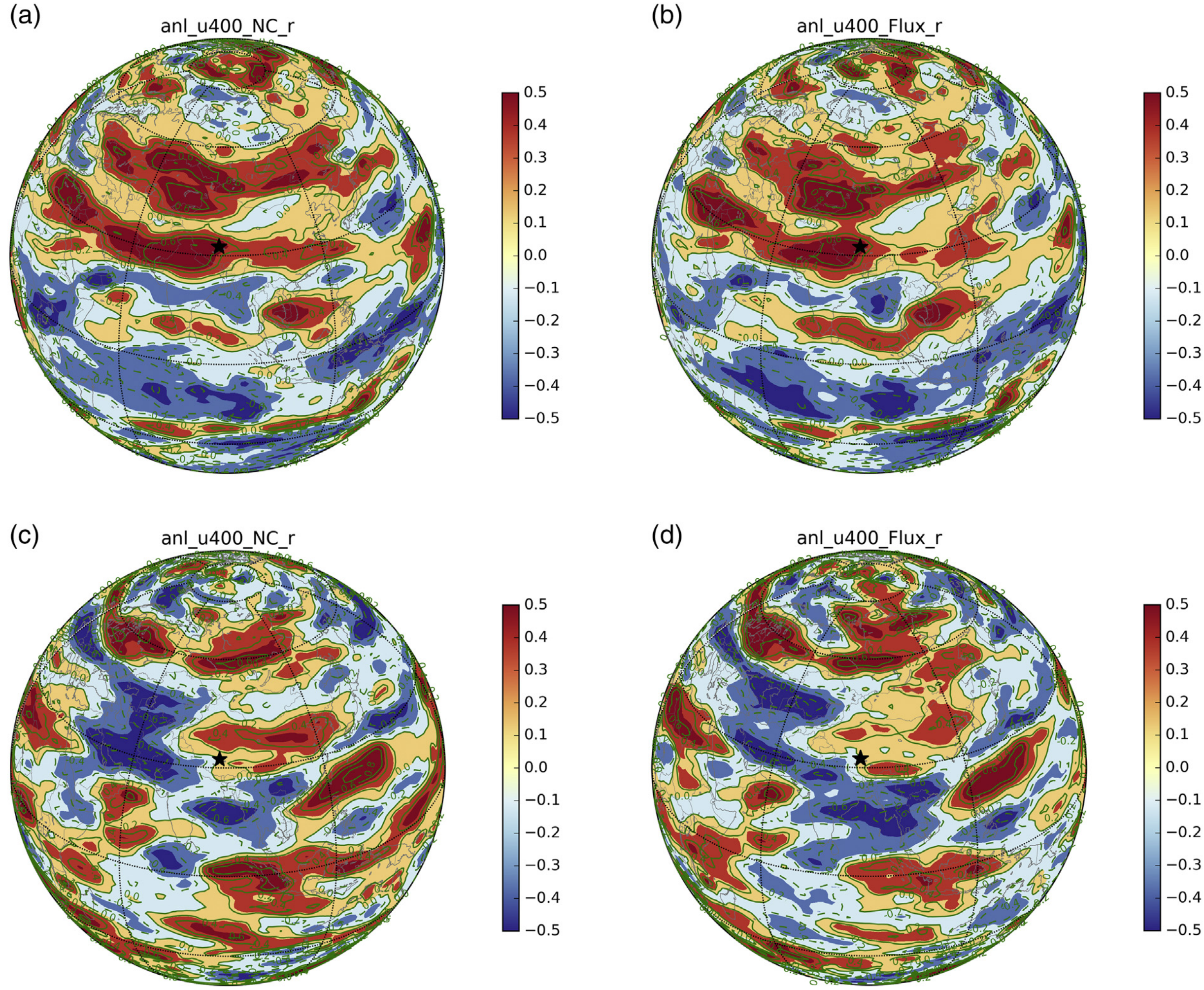

Fig. 7. Spatial correlation of dust number concentration (NC) and 400 hPa zonal wind (a), spatial correlation of dust flux and 400 hPa zonal wind (b) in the high dust period (1975–1987); same as in (a), (b) but in the low dust period (1988–2000) (c), (d).

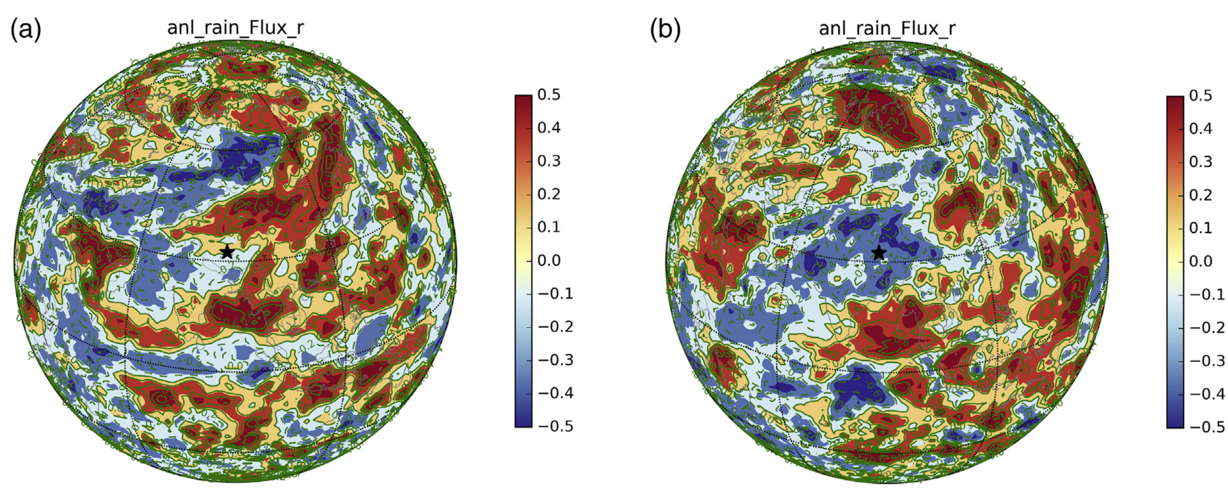

Fig. 8. Spatial correlation of dust flux and precipitation in the high dust period (1975–1987) (a) and low dust period (1988–2000) (b).

None of the dust concentration, flux or MND variability of the MGGQ ice core is correlated with the NAO or PDO (Fig. 9). This indicates that the relationship between dust and atmospheric circulation is complicated, and the relationship might change in different regions of the TP. Atmospheric circulation may affect the dust record by changing the wind (intensity and transport path) and humidity in the dust source area (Liu et al., 2016; Sun et al., 2001). The TP has experienced rapid warming and increased moisture since the beginning of the 1980s (Yang et al., 2014). The decline of westerly wind strength can be explained by atmospheric circulation adjustments, a result of differences in surface warming between Asian high- and low-latitudes (Grigholm et al., 2009; Jones et al., 2007). Combining dust records in ice cores

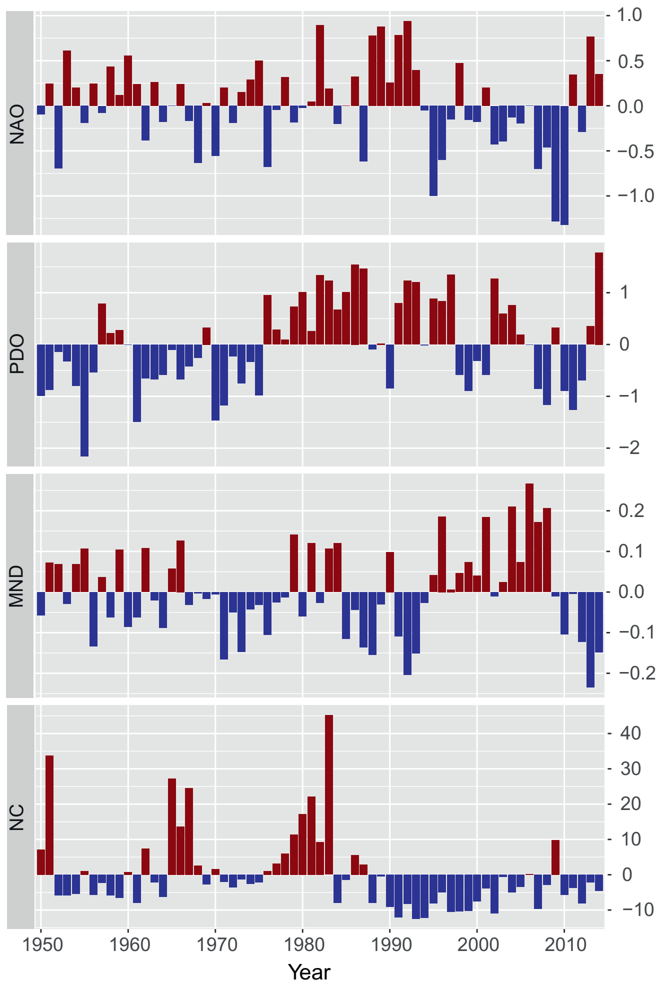

Fig. 9. Anomalies of NAO, PDO and dust mean number diameter (MND), number concentration (NC) in the Mugagangqiong Ice Core.

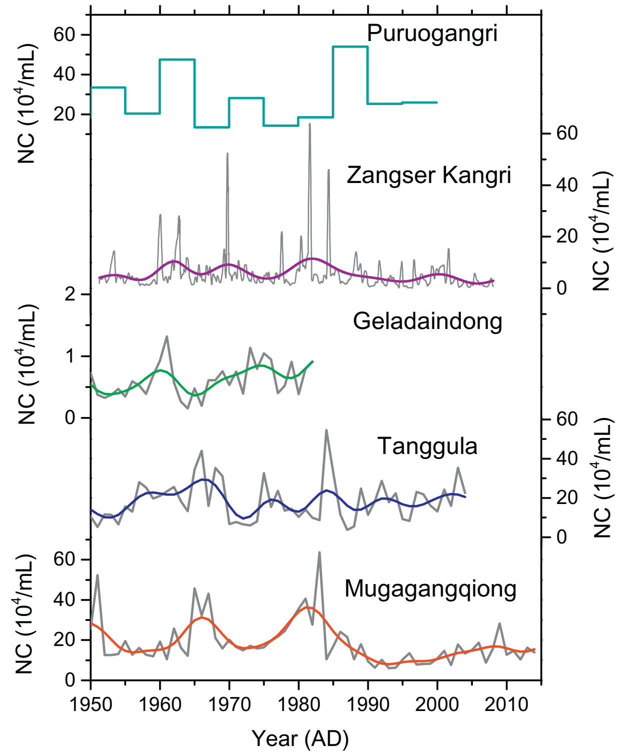

Fig. 10. Time series of dust concentrations in ice cores from 1950 to 2014 in the central Tibetan Plateau. (For Geladaindong, Tanggula, Mugagangqiong, grey lines represent annual average, coloured lines represent three-point smoothing of annual values; for Puruogangri, the coloured line represents five-year average values; for Zangser Kangri, the grey line represents the raw sample data, the coloured line represents three-point smoothing of annual values).

with modern observation data helps to gain new insights into the relationship between dust and atmospheric circulation.

3.5. Dust concentrations of different ice cores in the central Tibetan Plateau

The westerlies and the Indian monsoon interact in the mid-latitude (30–35°N) on the Tibetan Plateau. In this region, atmospheric dust varies due to the complexity of the atmospheric circulation controlling it. The dust records of five ice cores for the period 1950–2014, namely Puruogangri, Zangser Kangri, Geladaindong, Tanggula and Mugagangqiong from the central TP can be seen in Fig. 10. Detailed information of their dust record is presented in Table 2. In order to give a clear trend, the moving average of three years of the dust record was applied, with the exception of Puruogangri, where the average value of five years was applied. It can be seen that dust records of the ice cores in the central plateau have exhibited some similarities over the past few decades. The dust concentrations of Zangser Kangri, Tanggula, and MGGQ ice core were all high in the 1960s and 1980s, and low in the 1970s and 1990s. In the early 1960s and late 1980s, the dust concentration of the Puruogangri ice core was high, but low in the 1990s. The consistent variation in the trend of the dust records indicates enhanced aridity, strong winds and frequent dust storms in the 1960s and 1980s in this region. In addition, dust concentration remained at a low level in the 1990s, due to the weakened westerly wind and increased precipitation (as discussed in Section 3). However, apparent differences in the dust records of these five ice cores also exist. Geladaindong ice core, whose concentration is an order of magnitude lower than the rest (see Table 2), shows no similarity to the others. The time of peak of dust-loading of the five ice cores appears to be different (Fig. 10). Though the five ice cores are all located in the central part of the TP with similar altitudes, discrepancies in inter-annual variations of ice core dust records still exist and can be attributed to different contributions of local sources and to different atmospheric circulation patterns (e.g. westerly wind vs. Indian monsoon). It is reasonable to assume that the interactions between the westerly jet stream and Indian monsoon, as well as their transitions, have an important impact on dust source and transport, which leads to differences in the dust record in ice cores in this region (Zhang et al., 2015; Ferrat et al., 2011; Zhang et al., 2003). Dust records in ice cores might also be affected by the local environment. Therefore, it is of great importance to determine the sources of dust and their relative contribution in ice cores, and this should be a key objective of further research.

4. Conclusions

In this study, the change in atmospheric dust from 1950 to 2014 was reconstructed using the dust records of Mugagangqiong (MGGQ) Ice Core in the central Tibetan Plateau. The dust concentration of the MGGQ ice core is positively correlated with dust storm events in the Taklimakan Desert, and also positively correlated with dust observations at meteorological stations in the central plateau, indicating that the dust record of the MGGQ ice core is a good indicator for regional atmospheric dust variations. Between 1950 and 2014, two periods of dustiness, 1962–1968 and 1975–1987, are characterised by high dust concentration and flux, and coarse particle size, corresponding to enhanced aridity, strong winds and frequent dust storms. Dust concentration and flux decrease from the late 1980s, and 1988–2000 is the

Table 2
Characteristics of ice cores from the central Tibetan Plateau.

Ice Core	Latitude	Longitude	Elevation	Period	Particle size range	NC	MC	Flux	Reference
			m a.s.l	AD	μm	10^4/mL	μg/kg	μg cm^{-2} a^{-1}	
Mugagangqiong	32°14′N	87°28′E	6085	1950–2014	1–30	18.5	8239.1	110.15	This study
Tanggula	33°07′N	92°05′E	5743	1950–2004	1–30	18.38	10,058.9	219.82	Wu et al., 2013
Geladaindong	33°34′N	91°10′E	5750	1950–1982	1–30	0.61			Zhang et al., 2015
Puruogangri	33°55′N	89°05′E	6070	1950–2000	0.63–20	28.08			Thompson et al., 2006
Zangser Kangri	34°18′N	85°51′E	6226	1951–2008	2–30	4.84	3883		Zhang et al., 2016

period of the lowest dust concentration and flux. The highest (1975–1987) and the lowest (1988–2000) dust-loading periods were selected as two cases to investigate the possible dust mechanism using the JRA-55 reanalysis data. Results show that from 1975 to 1987, the strength of the westerly wind is the main control factor in determining dust variations in the central plateau. For the period 1988–2000, both decreased wind speed and increased precipitation in dust source areas (e.g. northwestern China) are responsible for the lowest dust-loads.

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Declarations of interest

None.

References

Bolzan, J.F., 1985. Ice flow at the Dome C ice divide based on a deep temperature profile. J. Geophys. Res. Atmos. 90, 8111–8124.
Chen, Y., Deng, H., Li, B., Li, Z., Xu, C., 2014. Abrupt change of temperature and precipitation extremes in the arid region of Northwest China. Quatern. Int. 336, 35–43.
Ferrat, M., Weiss, D.J., Strekopytov, S., Dong, S., Chen, H., Najorka, J., Sun, Y., Gupta, S., Tada, R., Sinha, R., 2011. Improved provenance tracing of Asian dust sources using rare earth elements and selected trace elements for palaeomonsoon studies on the eastern Tibetan Plateau. Geochim. Cosmochim. Acta 75, 6374–6399.
Forster, P., Ramaswamy, V., 2007. Changes in Atmospheric Constituents and in Radiative Forcing. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. pp. 129–234.
Fujita, K., 2007. Effect of dust event timing on glacier runoff: Sensitivity analysis for a Tibetan glacier. Hydrol. Process. 21, 2892–2896.
Goudie, A.S., 2009. Dust storms: recent developments. J. Environ. Manag. 90, 89–94.
Grigholm, B., Mayewski, P.A., Kang, S., Zhang, Y., Kaspari, S., Sneed, S.B., Zhang, Q.G., 2009. Atmospheric soluble dust records from a Tibetan ice core: possible climate proxies and teleconnection with the Pacific Decadal Oscillation. J. Geophys. Res. 114, D20118.
Grigholm, B., Mayewski, P.A., Kang, S., Zhang, Y., Morgenstern, U., Schwikowski, M., Kaspari, S., Aizen, V., Aizen, E., Takeuchi, N., Maasch, K., Birkel, S., Handley, M., Sneed, S., 2015. Twentieth century dust lows and the weakening of the westerly winds over the Tibetan Plateau. Geophys. Res. Lett. 42, 2434–2441.
Harada, Y., Kamahori, H., Kobayashi, C., Endo, H., Kobayashi, S., Ota, Y., Onoda, H., Onogi, K., Miyaoka, K., Takahashi, K., 2016. The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability. J. Meteorol. Soc. Jpn. 94 (3).
Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang, L., Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., Yan, H., Wang, G., 2017. Dryland climate change: recent progress and challenges. Rev. Geophys. 55 (3).
Ji, Z., Kang, S., Zhang, Q., Cong, Z., Chen, P., Sillanpää, M., 2016. Investigation of mineral aerosols radiative effects over High Mountain Asia in 1990–2009 using a regional climate model. Atmos. Res. 178–179, 484–496.
Jickells, T.D., An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., Brooks, N., Cao, J.J., Boyd, P.W., Duce, R.A., Hunter, K.A., Kawahata, H., Kubilay, N., laRoche, J., Liss, P.S., Mahowald, N., Prospero, J.M., Ridgwell, A.J., Tegen, I., Torres, R., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308, 67–71.
Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein, A., Parker, D., Rahimzadeh, F., Renwick, J.K., Rusticucci, M., Soden, B., Zhai, P., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., 2007. Observations: Surface and atmospheric climate change. Climate change 2007: the physical science. In: Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change, pp. 235–336.
Kang, S., Mayewski, P.A., Yan, Y., Qin, D., Yao, T., Ren, J., 2003. Dust records from three ice cores: relationships to spring atmospheric circulation over the Northern Hemisphere. Atmos. Environ. 37, 4823–4835.
Kang, S., Zhang, Y., Grigholm, B., Kaspari, S., Qin, D., Ren, J., Mayewski, P., 2010. Variability of atmospheric dust loading over the central Tibetan Plateau based on ice core glaciochemistry. Atmos. Environ. 44, 2980–2989.
Kaspari, S., Mayewski, P.A., Handley, M., Kang, S., Hou, S., Sneed, S., Maasch, K., Qin, D., 2009. A high-resolution record of atmospheric dust composition and variability since A.D. 1650 from a Mount Everest ice core. J. Clim. 22, 3910–3925.
Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K., Takahashi, K., 2015. The JRA-55 Reanalysis: General specifications and basic characteristics. J. Meteorol. Soc. Jpn. 93, 5–48.
Li, Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., Wang, T., Xue, H., Zhang, H., Zhu, B., 2017. Aerosol and boundary-layer interactions and impact on air quality. Natl. Sci. Rev. 4, 810–833.
Lin, C., Yang, K., Qin, J., Fu, R., 2013. Observed coherent trends of surface and upper-air wind speed over China since 1960. J. Clim. 26, 2891–2903.
Liu, W., Wang, L., Chen, D., Tu, K., Ruan, C., Hu, Z., 2016. Large-scale circulation classification and its links to observed precipitation in the eastern and central Tibetan Plateau. Clim. Dynam. 46, 1–17.
Maring, H., Savoie, D.L., Izaguirre, M.A., Custals, L., 2003. Mineral dust aerosol size distribution change during atmospheric transport. J. Geophys. Res. Atmos. 108, 1–6.
Ren, G., Yuan, Y., Liu, Y., Ren, Y., Wang, T., 2016. Changes in precipitation over Northwest China. Arid. Zone. Res. 33, 1–19.
Shao, Y., Dong, C.H., 2006. A review on East Asian dust storm climate, modelling and monitoring. Glob. Planet. Chang. 52, 1–22.
Sun, J., Zhang, M., Liu, T., 2001. Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960-1999: Relations to source area and climate. J. Geophys. Res. Atmos. 106, 10325–10333.
Tang, Y., Han, Y., Ma, X., Liu, Z., 2018. Elevated heat pump effects of dust aerosol over northwestern China during summer. Atmos. Res. 203, 95–104.
Tegen, I., Lacis, A.A., Fung, I., 1996. The influence on climate forcing of mineral aerosols from disturbed soils. Nature 380, 419–422.
Thompson, L.G., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., Bolzan, J.F., 1997. Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core. Science 276, 1821–1825.
Thompson, L.G., Yao, T.D., Mosley-Thompson, E., Davis, M., Henderson, K., Lin, P.N., 2000. A high-resolution millennial record of the south Asian monsoon from Himalayan ice cores. *Science* 289, 1916–1919.
Thompson, L.G., Mosley-Thompson, E., Brecher, H., Davis, M., Leo'n, B., Les, D., Lin, P., Mashiotta, T., Mountain, K., 2006a. Abrupt tropical climate change: past and present. Proc. Natl. Acad. Sci. USA. 103, 10536–10543.
Thompson, L.G., Yao, T.D., Davis, M.E., Mosley-Thompson, E., Mashiotta, T.A., Lin, P.N., Mikhalenko, V.N., Zagorodnov, V.S., 2006b. Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau. Ann. Glaciol. 43, 61–69.
Wang, N., 2005. Decrease trend of dust event frequency over the past 200 years recorded in the Malan ice core from the northern Tibetan Plateau. Chin. Sci. Bull. 50, 2866–2871.
Wang, R., Liu, B., Li, H., Zou, X., Wang, J., Liu, W., Cheng, H., Kang, L., Zhang, C., 2017. Variation of strong dust storm events in northern China during 1978–2007. Atmos. Res. 183, 166–172.
Wang, X., Liu, J., Che, H., Ji, F., 2018. Spatial and temporal evolution of natural and anthropogenic dust events over Northern China. Sci. Rep. UK. 8 (1), 2141.
Wu, G., Yao, T., Xu, B., Tian, L., Zhang, C., Zhang, X., 2009. Volume-size distribution of microparticles in ice cores from the Tibetan Plateau. J. Glaciol. 55, 859–868.
Wu, G., Yao, T., Xu, B., Tian, L., Zhang, C., Zhang, X., 2010. Dust concentration and flux in ice cores from the Tibetan Plateau over the past few decades. Tellus B. 62, 197–206.
Wu, G., Zhang, C., Xu, B., Mao, R., Joswiak a, D., Wang, N., Yao, T., 2013. Atmospheric dust from a shallow ice core from Tanggula: implications for drought in the central Tibetan Plateau over the past 155 years. Quaternary. Sci. Rev. 59, 57–66.
Xu, J., Hou, S., Qin, D., Kang, S., Ren, J., Ming, J., 2007. Dust storm activity over the Tibetan Plateau recorded by a shallow ice core from the north slope of Mt. Qomolangma (Everest), Tibet-Himal region. Geophys. Res. Lett. 34, L17504.
Xu, J., Hou, S., Qin, D., Kaspari, S., Mayewski, P.A., Petit, J.R., Delmonte, B., Kang, S.,

Ren, J., Chappellaz, J., 2010. A 108.83-m ice-core record of atmospheric dust deposition at Mt. Qomolangma (Everest), Central Himalaya. Quat. Res. 73, 33–38.
Xu, J., Yu, G., Kang, S., Hou, S., Zhang, Q., Ren, J., Qin, D., 2012. Sr-Nd isotope evidence for modern aeolian dust sources in mountain glaciers of western China. J. Glaciol. 58, 859–865.
Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., Chen, Y., 2014. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. Glob. Planet. Chang. 112, 79–91.
Yang, X., Shen, S., Yang, F., He, Q., Ali, M., Huo, W., Liu, X., 2016. Spatial and temporal variations of blowing dust events in the Taklimakan Desert. Theor. Appl. Climatol. 125, 669–677.
Yasunari, T.J., Koster, R.D., Lau, K.M., Aoki, T., Sud, Y.C., Yamazaki, T., Motoyoshi, H., Kodama, Y., 2011. Influence of dust and black carbon on the snow albedo in the NASA Goddard Earth observing System version 5 land surface model. J. Geophys. Res. Atmos. 116 (D2).
Zhang, Y., Carmichael, G.R., 1998. The role of mineral aerosol in tropospheric chemistry in East Asia-a model study. J. Appl. Meteorol. 38, 353–366.
Zhang, X.Y., Gong, S.L., Zhao, T.L., Arimoto, R., Wang, Y.Q., Zhou, Z.J., 2003. Sources of Asian dust and role of climate change versus desertification in Asian dust emission. Geophys. Res. Lett. 30, 5–8.
Zhang, Y., Kang, S., Zhang, Q., Grigholm, B., Kaspari, S., You, Q., Qin, D., Mayewski, P., Cong, Z., Huang, J., Sillanpää, M., Chen, F., 2015. A 500year atmospheric dust deposition retrieved from a Mt. Geladaindong ice core in the central Tibetan Plateau. Atmos. Res. 166, 1–9.
Zhang, W., Hou, S., An, W., Zhou, L., Pang, H., 2016. Variations in atmospheric dust loading since AD 1951 recorded in an ice core from the northern Tibetan Plateau. Ann. Glaciol. 57, 258–264.
Zhu, C., Wang, B., Qian, W., 2008. Why do dust storms decrease in northern China concurrently with the recent global warming? Geophys. Res. Lett. 35 (18).
Zielinski, G.A., Mershon, G.R., 1997. Paleoenvironmental implications of the insoluble microparticle record in the GISP2 (Greenland) ice core during the rapidly changing climate of the Pleistocene-Holocene transition. Geol. Soc. Am. Bull. 109 (5), 547–559.